

## The Evolution of Spiral Disks

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**Abstract.** We report on aspects of an observational study to probe the mass assembly of large galaxy disks. In this contribution we focus on a new survey of integral-field H $\alpha$  velocity-maps of nearby, face on disks. Preliminary results yield disk asymmetry amplitudes consistent with estimates based on the scatter in the local Tully-Fisher relation. We also show how the high quality of integral-field echelle spectroscopy enables determinations of kinematic inclinations to  $i \sim 20^\circ$ . This holds the promise that nearly-face-on galaxies can be included in the Tully-Fisher relation. Finally, we discuss the prospects for measuring dynamical asymmetries of distant galaxies.

### 1. Introduction

Tully-Fisher (TF) surveys at cosmological distances provide a direct way to track the evolution in fundamental scaling relations of disk galaxies. Such surveys permit, for example, the measurement of the disk size or luminosity evolution under the assumption that deviations from fiducial TF relations can be understood as photometric changes in constant-mass potentials. Deviations from TF may also be produced by dynamical asymmetries due to instabilities, interactions, minor mergers, or slow and possibly lumpy mass-accretion. Semi-analytic models of galaxy formation are able to reproduce the basic slope and scatter in the TF relationship at  $z = 0$ , yet most fail to recover the correct zero-point (e.g. Steinmetz & Navarro, 1999). We anticipate that in the future, however, the scatter in the TF relation will be a more useful diagnostic of how disks are assembled. The scatter about the TF relation should constrain the modes by which disks form, particularly if the nature of this scatter can be determined as a function of redshift. For example, are offsets from a fiducial TF relation accompanied by an increase in disk asymmetry?

### 2. Towards a Tully-Fisher Relation for Face-on Galaxies

Historically, TF surveys have targeted galaxies with photometric inclinations above  $40\text{--}45^\circ$  in order to minimize errors in the corrected rotation velocities. HI kinematic estimates of inclination also have been difficult to measure below  $i \sim 40^\circ$  given the precision of HI maps in the past, as well as the intrinsic problems associated with flaring and warping of the outer parts of HI disks (e.g. Begeman, 1989). We have recently acquired integral-field echelle spectroscopy with the WIYN telescope's Densepak fiber-bundle of over a dozen, nearby disk

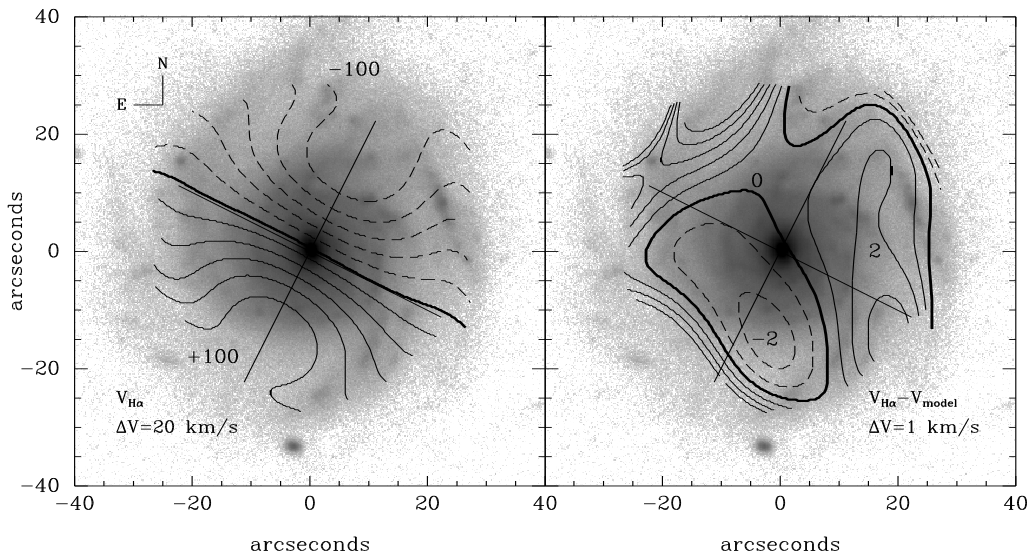


Figure 1. WIYN/Densepak H $\alpha$  velocity-field for PGC 46767 (**left**), and the residuals from a single, inclined, rotating disk model (**right**). The kinematic major and minor axes are drawn for reference. Note the *low* amplitude, yet coherent structure of the velocity residuals. Also note the large projected velocity for a (photometrically) apparently face-on disk.

galaxies ( $0.02 < z < 0.05$ ). An example is shown in Figure 1. In as little as an hour apiece we have obtained high quality, H $\alpha$  velocity fields at a precision of  $\sim 2$  km/s over the inner 2-3 few scale lengths of each disk. Moreover, we have been successful fitting single, inclined disks to these kinematic data; residuals are typically  $\sim 3.5$  km/s (rms). The derived kinematic inclinations compare favorably to those estimated from inverting the optical-HI TF relation (Figure 2, right panel). We estimate that the kinematic inclinations from WIYN/Densepak H $\alpha$  maps can be measured to better than 10% down to  $i = 25^\circ$ ; the dominant error appears to arise from non-circular motions in the disks (Figure 3). The excellent correlation in Figure 2 (right panel) indicates, however, that our error estimates may be substantially too conservative! The ability to study galaxies at low, but precisely known inclinations is of interest for TF work because (i) detailed disk structure can be viewed with little projection, and (ii) the vertical component of the disk velocity ellipsoid is favorably projected for measurement (potentially enabling estimates of both total and disk mass).

### 3. Disk Asymmetry in the Nearby Universe

By combining two-dimensional, kinematic information with optical and near-infrared images of disks, one can explore in detail the asymmetry of disks. The kinematic exploration has long been the domain of HI studies (e.g. Richter & Sanchisi 1994, Haynes et al. 1998, Swaters et al. 1998), but now this can be done routinely in HII and folded more directly into optical studies of photometric asymmetries (e.g. Zaritsky & Rix 1997; Kornreich et al. 1998; Conselice et al. 2000). The next step, of course, is to be able to make comparable kinematic measurements for the *stellar* component of disks.

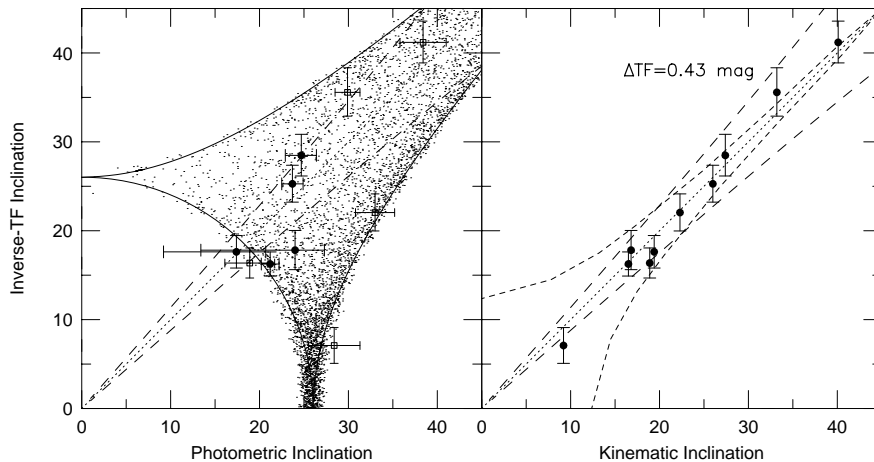


Figure 2. A comparison of inclination angles derived from inverting the TF relation (given observed HI line-width from Paturel et al. 1997, and  $B$  apparent magnitude from the RC3) versus: (i) photometric inclinations based on WIYN  $R$  and  $I$  band images (**left** panel); and (ii) inclinations from modeling two-dimensional  $H\alpha$  velocity fields from WIYN/Densepak (**right** panel). Short and long-dashed lines are expected  $1\text{-}\sigma$  uncertainties for kinematic and inverse-TF inclinations, respectively. Solid lines (left panel) are the region accessible for disks with 10% intrinsic ellipticity; dots represent a Monte Carlo representation of a random sampling of such disks.

Comparisons of the kinematic to photometric inclination and position angles can yield constraints on the intrinsic ellipticity of disks. As a simple test, we compare inclination angles in Figure 2. If disks are intrinsically elliptic at the 10% level (a limit inferred from the scatter in the TF relation; Franx & de Zeeuw, 1992), then there will be an overabundance of apparently (photometrically) inclined galaxies which are kinematically close to face-on. The small sample studied to date is consistent with intrinsic disk ellipticities  $\leq 10\%$ . More powerful constraints lie in extracting apparent ellipticities relative to kinematic major and minor axes (Andersen et al., in preparation).

#### 4. Measuring Disk Asymmetry at Higher Redshifts

Velocity fields of distant disk galaxies would provide direct evidence of their evolving dynamical states. However, the combined distance effects of shrinking size, cosmological surface-brightness dimming, and redshifting of spectral features into spectral regions of higher terrestrial sky-backgrounds makes such observations daunting. Assuming that one samples the same physical scale at all distances, the product of the telescope diameter and observing-time<sup>1/2</sup> goes roughly as  $(1+z)^{4.25}$  from the ground, in the background limit, at high spectral resolution, and at  $z > 0.7$  (where apparent size is a weak function of redshift). Only modest gains ( $-1.25$  in the exponent) are made from space.

A zero-point for this telescope-diameter-time-redshift relation can be set from the Keck observations of rotation curves at  $z \sim 1$ , taken in several hours with a 1 arcsec wide slit (Vogt et al. 1997). A factor of 3 higher spatial resolution would just resolve galaxies at cosmological distances at the equivalent of one disk

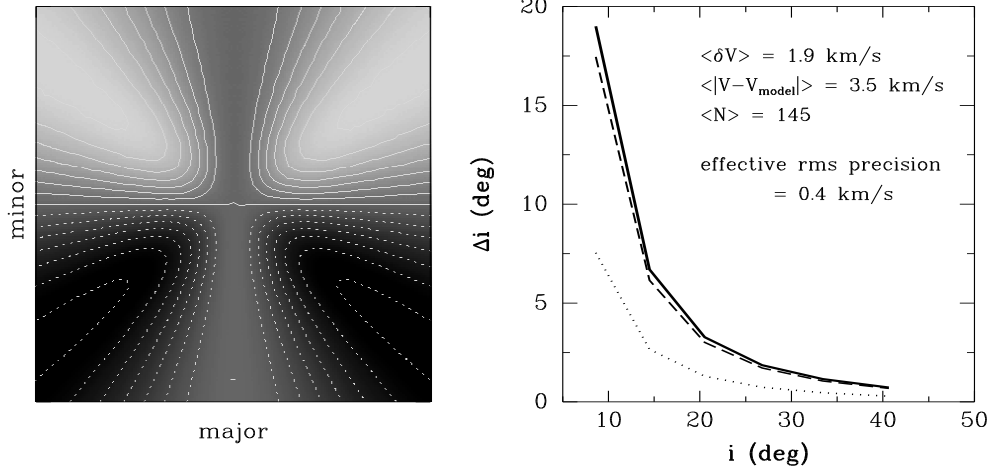


Figure 3. The velocity-field residuals (**left**) between two rotating disks at inclinations of  $10^\circ$  and  $20^\circ$  shows the maximum sensitivity to inclination lies at  $\theta \sim \pm 45$  from the kinematic major axis. For our characteristic instrumental precision ( $\delta V$ ), observed residuals ( $V - V_{\text{model}}$ ), and number of beams per galaxy (fibers,  $N$ ), the **right** panel shows our estimated precision ( $\Delta i$ ) as a function of true inclination for deriving kinematic inclinations from WIYN/Densepak H $\alpha$  echelle spectroscopy for our nearby galaxy sample.

scale-length for a typical disk today. In the background limit, one would then require a three times larger aperture at constant exposure time, i.e. a 30-m telescope. Other gains can come from (i) improved instrument throughput, and (ii) enhancing surface-brightness contrast by resolving bright, star-forming knots in distant galaxy disks via high-order adaptive optics (Koo, 1999). The latter is not applicable, however, for the study of stellar motions in disks, which are of particular interest for understanding asymmetries in disk mass distributions.

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